

INVESTIGATION OF THE HERMETICITY OF BCB-SEALED CAVITIES FOR HOUSING (RF-)MEMS DEVICES

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ABSTRACT

This paper reports on the hermeticity testing of MEMS cavities using BCB as the sealing and bonding material. Hermeticity has been tested according to the MIL-STD-883D. Gross leak testing based on liquid fluorocarbons revealed that BCB sealed cavities are leak tight, which means that the MEMS devices are well protected during handling and back-end processing (e.g., wafer dicing). Further, it is shown that the He fine leak testing of the MIL-STD is not fully applicable to small volumes (<1000nl), typically encountered for MEMS. The problem is that the undefined regime normally existing in the MIL-STD is largely extended for small cavity volumes. Microbolometers have been used as test vehicles to confirm this. Large (>10,000nl) cavities are needed to cover the entire leakage spectrum.

INTRODUCTION

MEMS devices, such as microresonators, microbolometers and RF-MEMS switches, contain movable and fragile structures that must be encapsulated not only for protection during (back-end) processing, but also to ensure stable and reliable performance characteristics. It is generally required that (part of) the packaging is carried out on the wafer during wafer processing, prior to die singulation as standard wafer sawing will destroy the MEMS device. Fig.1 gives an example of on-wafer encapsulation of a RF-MEMS device in a sealed cavity by using wafer or chip stacking techniques.

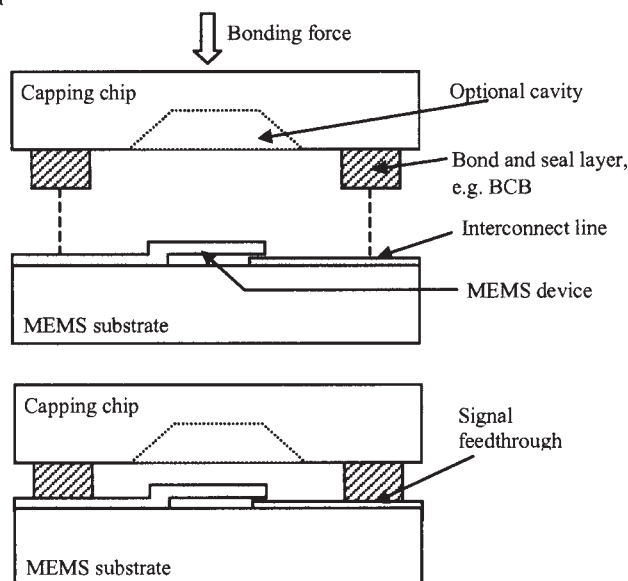


Figure 1. Illustration of on-wafer encapsulation of a MEMS device in a sealed cavity using chip stacking techniques.

It is generally required that the housing cavity is mechanically strong, hermetic, and does not degrade the device performance. BenzoCycloButene (BCB), a commercially available polymer from Dow Chemical [1], is a potential candidate for the adhesive bonding and sealing layer [2,3]. Compared to anodic bonding or silicon direct bonding, using BCB for the bonding and the sealing

material defines a relatively simple process. In particular the liquid-like behavior of BCB observed during curing [2] makes the sealing of cavities with protruding signal feedthroughs rather straightforward. Moreover, BCB displays minimal outgasing, low moisture uptake, high chemical resistance, high bond strength, low processing temperature (< 250°C), and low residual stress levels. Furthermore, its high resistivity ($10^{19} \Omega\text{cm}$), low loss tangent (0.0008-0.002 in the range 1MHz-10GHz) and low permittivity (2.65) make BCB a very good candidate for high frequency (RF-MEMS) applications [4,5].

Although BCB has been characterized in great detail [1,2], not much has been said about its sealing properties, and particularly its hermeticity. In this paper, the hermeticity of cavities sealed with BCB is further investigated. Starting point for the hermeticity tests is the procedure described in Method 1014.9 of Military Standard MIL-STD-883D [6]. Hermeticity testing requires both gross and fine leak testing to be carried out. Because MEMS packaging deals with volumes (0.001nl-1000nl) much smaller (at least 1000 times smaller) than the volumes described in the MIL-STD-883D, He leak detection is not very applicable for such devices [7] as it will be explained in this paper. In order to investigate the hermeticity of BCB bonds, we have used fine leak and gross leak tests on empty cavities and used microbolometers [8] and MEMS resonators [9] as test vehicles.

FABRICATION PROCEDURE AND SAMPLE PREPARATION

Process flows

Two different process flows for fabricating BCB-sealed cavities are developed. In both flows, the capping wafer is processed independently from the MEMS wafer. Figure 2 shows the steps of both flows, illustrated for a RF-MEMS switch [5]. In the first flow, a cavity sealed with a controlled ambient can be realized, and is referred as the 'BCB-IRS' method (BCB-Indent Reflow Sealing). It is based on a technique developed initially for solder bonding [10]. A thick enough layer of photosensitive BCB (CYCLOTENE series 4000) is spin coated on the cap wafer and patterned to make rings of various dimensions (typically 250-350 μm wide, 1-5 mm in side). The capping wafer is diced and the individual capping chips are flip-chip pre-bonded (typically 120°C, 250gf, 3min, at air ambient) onto the MEMS wafer (see Fig. 2(b)). The temperature of 120°C is well below the curing and reflow temperature of the BCB [1], leaving the slots or spaces open in between the protruding lines. The MEMS wafer with the packaged devices is next transferred to a reflow oven. The oven is evacuated and filled with the desired gas and pressure.

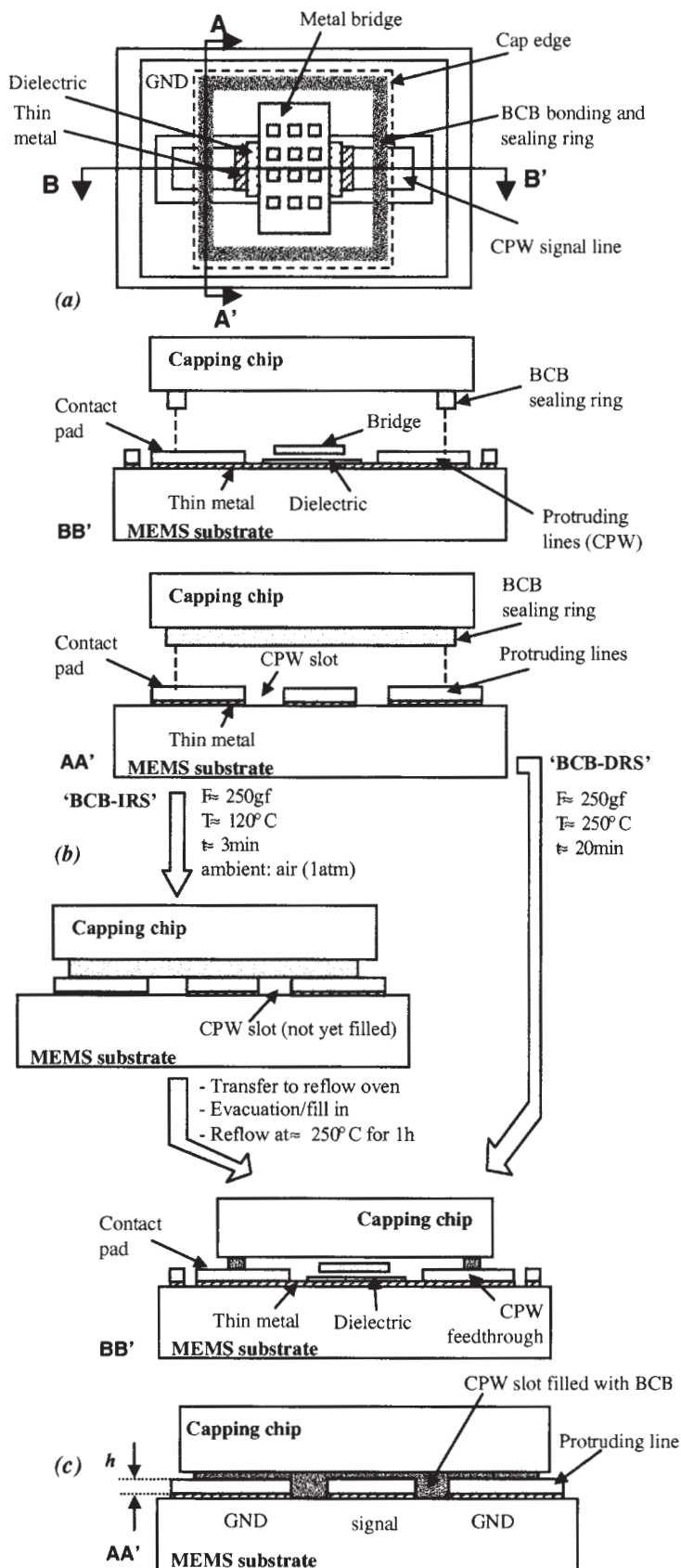


Figure 2. Illustration of 'BCB-IRS' and 'BCB-DRS' process flows. Shown is an RF-MEMS switch consisting of a metal bridge suspended over a coplanar wave guide (CPW) line [5].

Next, the temperature is raised to 250°C for 1 hour. The BCB starts to flow, and the slots are filled as shown in Fig.2(c). The second process flow is referred to as the 'BCB-DRS' process (BCB-Direct Reflow Sealing). The process is very similar to 'BCB-IRS', except that there is no pre-bonding step, and the curing/reflow of BCB is done directly during the flip-chip assembly at 250°C and at atmospheric pressure for 20min as illustrated in Fig. 2. The final structure shown in Fig.2(c) is basically the same for both process flows.

Sample preparation

Microbolometers (Fig.3) and microresonators have been packaged according to the schemes in Fig. 2. A 10µm thick spin coated BCB layer has been used. Both types of devices have protruding signal lines. Also empty cavities have been fabricated using the 'BCB-DRS' process flow thereby using a 5µm thick BCB layer. The empty cavity structures present a perfectly planar bonded surface, eliminating any influence of protruding lines as for the microbolometers or the microresonators.

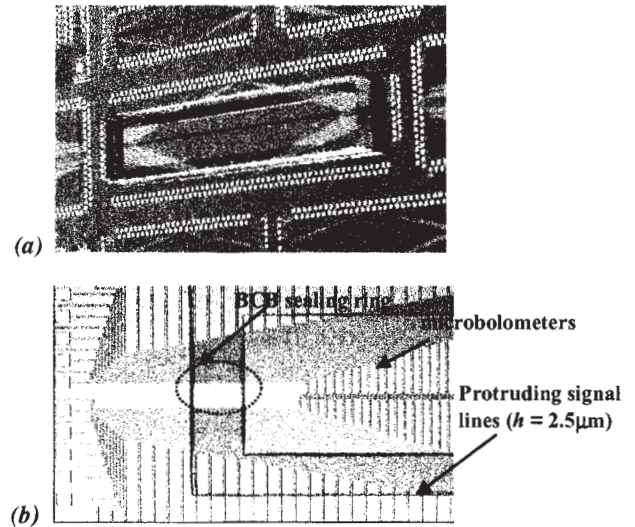


Figure 3. Packaged linear arrays of polySiGe bolometers using a borosilicate (AF45) glass cap. (a) Global view. (b) Close-up view.

LEAK/HERMETICITY TESTING

According to Method 1014.9 of MIL-STD-883D, hermeticity testing requires both gross and fine leak testing [6]. Gross leaks are tested using fluorocarbon liquids (FC-84 and FC-40) and are based on the "bubble method". For this, the sample is placed in FC-84 (boiling point: 80°C) for several hours. Next, the sample is dried and immediately transferred to FC-40 (boiling point: 139-189°C) heated to a temperature of about 110°C. The presence of FC-84 inside the cavity, and thus, the existence of a gross leak, is observed as 'stream' of bubbles of FC-84. Leaks exceeding 10⁻⁴ mbar.l/sec are generally termed gross leaks [6]. The fine leak test consists of a "He-leak check". This test is always carried out before the gross leak test. The test consists of pressurizing the sample with a high pressure of He, e.g. 3 bars absolute pressure, for several hours. Next, the

samples are transferred to a He mass spectrometer where the He leak rate is measured. According to the above, the spectrum of leak rates is broadly divided into two regimes as shown in Fig. 4.

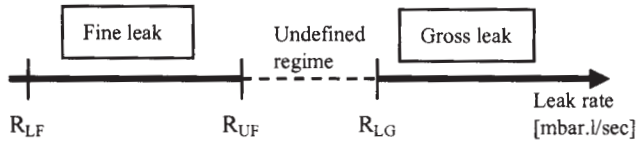


Figure 4. Leak rate spectrum. The subscripts LG, LF and UF stand for Lower Gross leak, Lower Fine leak and Upper Fine leak, respectively.

It is useful to investigate the sensitivity limits of both fine leak and gross leak detection, since they determine the leak range which can be covered. The gross leak test covers leak rates above $R_{LG}=10^{-4}$ mbar.l/sec [6]. The lower limit R_{LF} of the fine leak test is given by the lower sensitivity of the He leak detector ($R_{LF} \approx 0.4 \times 10^{-9}$ mbar.l/sec). But more important is the upper limit R_{UF} of the fine leak test. It cannot be easily defined as it is a function of the cavity volume to be tested.

The pressure change per unit time in the cavity is approximately given by [7]:

$$\frac{\Delta p(t)}{\Delta t} \approx \frac{r}{V} \quad (1)$$

where $\Delta p(t)$ is the differential pressure between inside and outside of the cavity, as a function of time t ,

V is the volume of the cavity,

and $r=r(\Delta p(t))$ is the leak rate being a function of $\Delta p(t)$.

In the leak rate tests, Δt represents the dwell time or transfer time necessary to take the sample out of the He overpressure chamber, and to start the He leak detection. If during this dwell time, the He is leaking out of the package, we will not be able to measure any He signal in the leak detector. With $\Delta p=3$ bars, such a leak becomes: $3000[\text{mbar}] \times V[l]/\Delta t$. Figure 5 is an illustration of the volume dependence of R_{UF} for different dwell times Δt .

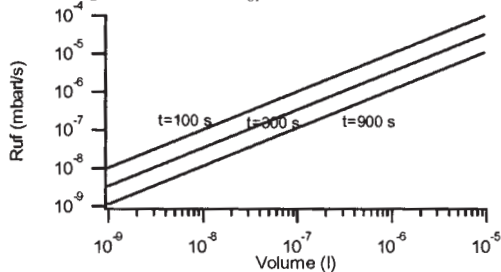


Figure 5. Dependence of the upper fine leak rate R_{UF} on the cavity volume V for a dwell time of 100, 300 and 900sec.

It becomes clear that, for a volume of 100nl and a reasonable dwell time of 300s, the upper limit R_{UF} of the fine leak detection is about 10^{-6} mbar.l/s. This is two orders of magnitude lower than the lower limit R_{LG} of the gross leak test. In other words, for such small volumes, the leak range between 10^{-6} and 10^{-4} mbar.l/sec is not covered by the combination of fine and gross leak test. By using MIL-STD-883D for a volume as small as 100nl, a leak in the range of the detection limit of the He detector ($\approx 0.4 \times 10^{-9}$ mbar.l/s) might be interpreted in 2 ways:

① The leak might be effectively as low as 0.4×10^{-9} mbar.l/s.

② The leak might be much higher than the measured value and be in the undefined regime between R_{UF} and R_{LG} . If this is the case, the cavity will be completely evacuated in less than 5 minutes (a few seconds in case the leak is 10^{-4} mbar.l/sec). Since the dwell time must be much shorter than this, this is practically impossible.

Another problem for small cavities is the stringent leak rate requirement. For instance, for a cavity volume of 100nl, eq. (1) predicts a pressure increase inside the package of 345mbar during one day for a leak rate as low as the detection limit (0.4×10^{-9} mbar.l/s)! In fact, the evacuated cavity will become filled in a few days if placed in an ambient of 1bar (He). This is clearly not acceptable. If one requires a pressure increase smaller than 1mbar over a period of one year, the leak rate must be smaller than 3×10^{-15} mbar.l/s. Such leak rates cannot be measured by the He leak test. Other methods have to be developed, e.g., the FTIR method proposed by Nese *et al.* [7]. In this paper, microbolometer structures are proposed as explained below.

TEST RESULTS AND DISCUSSION

Empty cavities, microbolometers and microresonators have been used as test vehicles. An overview of the test results of all test vehicles is summarized in Table 1.

Table 1. Test results based on Method 1014.9 of MIL-STD-883D

Device	Volume [nl]	Process	Fine leak [mbar.l/s]	Gross leak
Bolometer	60	BCB-IRS	$1-2.6 \times 10^{-9}$	no
Empty cavity	5-60	BCB-DRS	$\pm 2 \times 10^{-9}$	no

Empty cavity testing

Empty cavities have been fabricated according the “BCB-DRS” method shown in Fig. 2, but without any protruding interconnecting lines. Twenty empty cavities have been testes according to MIL-STD-883D. The volumes varied from 5 to 60nl. Leak rates in the range 0.4×10^{-9} mbar.l/s- 4×10^{-9} mbar.l/sec have been found, and no gross leak could be detected.

Microbolometers testing

Microbolometers with protruding signal lines (2.5 μ m height) as shown in Fig. 4 have been capped using the BCB-IRS process. The cavity volume is approximately 60nl. A standard He leak test has been carried out on 8 samples. Measured He fine leak rates range from 1 to 2.6×10^{-9} mbar.l/sec. The second experiment carried out on the microbolometers consists of directly monitoring the time response of the devices acting as miniature Pirani gauge pressure sensors as shown in Fig. 6. The measured output of the bolometers in air and vacuum is shown in Fig. 7. The packaged samples are placed individually in a vacuum chamber where the ambient pressure can be varied from atmospheric pressure to 10^{-3} mbar. It was found that a pressure variation in the chamber is monitored by all packaged microbolometers, hence indicating that all tested devices are leaking! By going back and forth from vacuum to 1 atmosphere in the chamber, it is observed that the bolometers follow the

ambient pressure within a few seconds. An estimate for the leak rate is obtained from Eq. (1) and is found to be larger than 6×10^{-9} mbar.l/sec. Finally, a gross leak test has been carried out on all packaged microbolometers. After pre-bonding at 120°C, bubbles have been observed indicating a gross leak. This is as expected since the slots between the protruding lines are still open. After reflow of BCB at 250°C, the bubbles were no longer observed. In other words, the gross leak disappeared, thus indicating that the BCB effectively fills the slots. Based upon the above tests, it can thus be concluded that a leak effectively exists and must be within the undefined regime of Fig.4 contrary what the MIL-STD indicates.

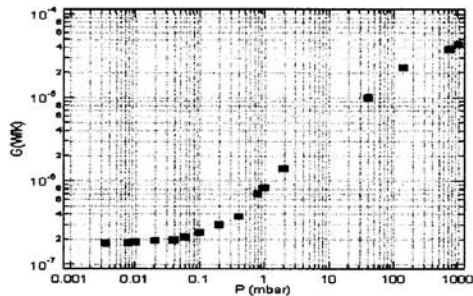


Figure 6. Pressure dependence of the thermal conductance G of a microbolometer.

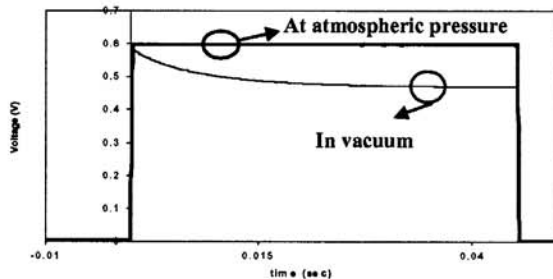


Figure 7. Time response of a BCB capped bolometer, measured at atmospheric pressure and in vacuum.

Microresonators testing

The Q-factor of a microresonator is a function of the pressure inside the cavity and can be extracted from the one-port impedance measurement (see Fig. 8).

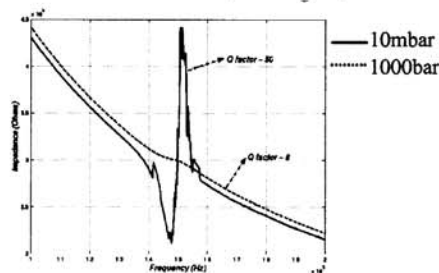


Figure 8. Impedance of a capped microresonator placed in a vacuum chamber and at atmospheric pressure.

Microresonators (volume ≈ 90 nl) have been packaged using the 'BCB-IRS' process of Fig. 2. The reflow is carried out in vacuum. The first indication that the package is leaking is that the Q-factor measured is around 8, whereas the Q-factor under vacuum is around 50. Secondly, by placing the microresonators in a vacuum chamber it was found that pressure variations are

followed within a few seconds by the resonators as indicated by the impedance response (as in Fig. 8).

CONCLUSION

A theoretical analysis has shown that the Method 1014.9 of MIL-STD-883D is not applicable to MEMS packages due to their small volume. Firstly, the upper detection limit of the fine leak test is well below the lower limit of the gross leak test for volumes below 1000nl. The latter effect has been demonstrated using BCB capping of MEMS microbolometers and microresonators. Both tests showed no fine nor gross leak, but investigating the characteristics of the MEMS devices indicated a leak in the package. Hence, we conclude that there has to be a leak in the range not covered by the fine and gross leak tests. It is still unclear whether this leak is due to gas permeation through the BCB, or due to leaks at the bonded surfaces. Further, the detection limit of the He leak detector is too high. An unacceptable pressure variation of 1mbar over a period of 1 year can be caused by a leak as small as 10^{-12} mbar.l/sec, which is 2 orders of magnitude lower than the detection limit of the fine leak test. In order to test the hermeticity of empty BCB sealed cavities, cavities with no topography and a size large enough in order to eliminate the undefined regime between fine and gross leak range are needed.

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